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LCA FOR ENERGY SYSTEMS

Life cycle assessment of electricity transmission and distribution—part 1: power lines and cables

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Abstract

Purpose The purpose of this study is to provide life cycle inventory data and results for components of electrical grids to the larger community of life cycle assessment practitioners. This article is the first in a series of two, each focusing on different components of power grids. In part 1, the objects under scope are power lines and cables. Systems for overhead, underground, and subsea transmission are modeled here, including HVDC systems used in long-distance transmission.

Methods We use process-based life cycle assessment based on information provided by companies and in reports, Ecoinvent v2.2 as a background dataset and ReCiPe Midpoint Hierarchist perspective v1.0 as the impact assessment method. The average European power mix is used to model the electrical energy required to compensate power losses in the equipment.

Results and discussion Under the assumption of European power mix, power losses are the dominant process for impacts of lines and cables in all impact categories, contributing with up to 99% to climate change impacts. An exception is the category of metal depletion, for which the production of metal parts is the most relevant process.

Conclusions After power losses, processes generating the most impacts for overhead lines are the production of metals for masts and conductors; production of foundations comes third. Recycling of metal parts shows benefits in all impact categories. For cables, infrastructure impacts are dominated by cable production, and recycling of cable materials does not always compensate for the other impacts generated at the end of life.

Keywords Electricity transmission · Environmental impacts of energy systems · Life cycle assessment · Power lines and cables

1 Introduction

The goal of this article is to inventory and characterize the life cycle environmental impacts from different electrical components in power grid systems. The supply of power involves generation, transmission, and distribution (T&D)—all of which have an associated environmental impact. The impact of delivering electricity to a Danish consumer was estimated to be 90% attributed to power production, 8% to distribution, and 2% to transmission (Cigré 2004a). For each country, these percentages will vary depending on factors such as the total power losses in the grid—or overall grid system efficiency, the power generation mix that is used to compensate for power lost in the grid, and distances from the power plants to the consumption site. Life cycle environmental impacts of several forms of power generation, including fossil or renewable based are well documented in the existing life cycle assessment (LCA) literature (Pfister et al. 2011; Weber et al. 2010; Schreiber et al. 2009; Phumpradab et al. 2009; Martinez et al. 2009; Lenzen 2008; Weisser 2007; Gagnon et al. 2002; Lenzen and Munksgaard 2002). However, LCA literature and data on electric power systems used for transmitting and distributing power are scarce, despite the fact that T&D is responsible for a significant share of total electricity supply chain impacts.

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With this article, we contribute to a common understanding of the environmental consequences resulting from power T&D. This is important, in particular considering the changes the power sector is likely to face in the future. Climate change mitigation policies call for an expansion in production of intermittent renewable power, which requires an upgrade or reinforcement of the current electrical grid system (Kempton et al. 2010) or new storage technologies. Renewable resources are often located far from consumption centers (BERR 2010), a situation which demands power grid expansion (for example in offshore areas), involving additional costs, material and energy requirements—and hence expected increases in environmental impacts. To address the real consequences of renewable energy supply, the impacts for T&D need to be included in the assessment.

For this study, we use LCA data gathered from different literature sources to establish inventories for different electrical grid components and analyze them using the recent ReCiPe impact assessment methodology (v1.0, Goedkoop et al. 2009). Part 1 of this paper covers the analysis for power lines and cables. In part 2, a similar analysis is provided for electrical transformers and equipment used in substations. We expect that over the lifetime of the equipment, power losses are a major contributor to overall impacts. T&D equipment losses represent a significant additional demand for generation. According to data from IEA for 2005, Japanese power grid losses accounted for 5% of the gross electricity, making Japan one of the most efficient countries in power T&D. In India, grid losses consume as much as 25% of the total power production (Gielen 2008). In this study, we aim to answer two research questions: how large are the impacts resulting from power losses in the equipment and how large is the share of impacts associated to each of the other life cycle stages: raw materials production, transportation, installation, maintenance, and dismantling. Although the impacts from power losses will vary with the power mix, we want to get an idea of how large this contribution is, for an average case, so here the power needed to compensate for losses in the equipment is estimated and modeled as the average European power mix (Ecoinvent Centre 2007b). In addition to addressing the research questions described, this study provides life cycle inventory (LCI) data and results which can be useful for future studies including T&D systems. The different components modeled here can be assembled to a grid system, for example an offshore wind farm grid connection, and the resulting life cycle impacts can be calculated.

1.1 State of the art in LCA for electrical power transmission and distribution systems

There are few peer-reviewed publications on the environmental impacts of T&D. The currently available studies are mainly produced by private companies, LCA database providers, and collective entities. The earliest studies were performed in the 1990s by utility companies, such as Vattenfall (1999) and Eltra, which is currently Energinet.dk (Eltra 1999a). Companies producing electrical grid components, in particular ABB (2011), have also prepared environmental product declarations for some of their devices. More recently, LCI data on transmission systems also became available through LCA databases such as Ecoinvent (Ecoinvent Centre 2007a). Ecoinvent v2.2 models electricity production, transmission, and supply, including four voltages of electrical network: low-voltage distribution network, medium-voltage transmission, high-voltage transmission, and long-distance transmission network. Life cycle assessment results for the Swiss grid are provided in the supplemental information. One of the limitations of the Ecoinvent dataset is that it is not possible to assign inputs or emissions to a specific component in the grid system (e.g., for a transformer or a power line), since the inventory data refer to the grid system as a whole. Another limitation is that the inventories for all countries are based on the Swiss network, which can have different characteristics from other grids. Here, we create an inventory for grid components which allows for modeling of individual components and also situation-specific grid systems. The International Council on Large Electric Systems—Cigré has published a few LCA reports on components of the electrical grid, including an LCA study for overhead lines (Cigré 2004a), a study for electrical power supply using SF_6 technology (Cigré 2004b), and a study on high-voltage power cables (Cigré 1996). The Electrical Power Research Institute (EPRI 2010) has identified T&D environmental consequences on their research portfolio for 2011, focusing on issues such as vegetation management and rights of ways, T&D facilities and equipment. In two recent peer-reviewed studies, LCA methods have been applied to assess the environmental burdens of transmission (Harrison et al. 2010) and distribution systems (Bumby et al. 2010). The former assesses the transmission grid in Great Britain, while the later focuses on overhead and underground distribution systems in southern California. Also in Blackett et al. (2008), LCA techniques are used to assess the environmental burdens of current and alternative materials for electricity transmission. In Jones and McManus (2010), power losses are modeled for high-voltage distribution overhead and underground lines. In this paper, losses are also modeled explicitly for the different types of components in electrical transmission/distribution systems. This overview shows that interest on T&D environmental issues is picking up and that both researchers and institutions are aware of the relevance of these matters in the current power sector context.

2 Methods and data

2.1 Scope and functional unit

The product systems modeled here are listed in Table 1 and include power lines and cables used for overhead, subsea, and underground transmission of power. The functional unit is 1 km of power line or cable operating during the lifetime. LCI data on resource use and emissions for production of materials, installation, maintenance, and end of life were provided by the Danish utility company Energinet.dk (Eltra 1999b, c, d, e, f). No data referring to line/cable manufacturing (assembly of components) were available, and hence this process was not included. However, results for transformers where manufacturing is modeled explicitly (part 2) indicate that these impacts are a very small fraction of the total, representing less than 0.03% of the total score for GWP100. This is because losses are responsible for over 96% of total impacts for transformers, and even if losses are left out, the other most important processes are production of raw materials and transportation. For lines and cables, losses also represent over 96% of total impacts. Therefore, the impacts of manufacturing will also be very small in this case and can be left out without compromising the validity of the results.

Detailed inventories for all lines/cables with data on all included processes are available in the Electronic supplementary material (Tables S5–S17). Power losses in the equipment have been estimated according to information on the electrical properties (Tables S3 and S4). There are many factors influencing losses for a particular grid system (e.g., voltage level, total circuit distance, loads, temperature, etc.), and the calculation of losses can become a complex exercise (Negra et al. 2006). For example, losses in HVDC are lower than the ones for HVAC, but only after a "break-even" distance, and that is why HVDC is only used in long-distance transmission. Modeling a specific grid system would always require collection of data on system losses on a case-to-case basis.

2.2 LCA model details

Process LCA (Rebitzer et al. 2004) was used to evaluate the impacts in each life cycle stage of the components. The LCA model used here includes a foreground system which is matched and linked to a background system, the matrix of Ecoinvent v2.2 (Ecoinvent Centre 2007a) unit processes. Life cycle environmental impacts have been obtained with the ReCiPe method. This method was chosen since it is the most complete and up-to-date impact assessment method. Here, we use the ReCiPe Midpoint Hierarchist perspective v1.0 (Goedkoop et al. 2009), for the different impact categories: climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine eutrophication, metal depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, terrestrial acidification, and terrestrial ecotoxicity. Marine ecotoxicity is not included, due to high uncertainty in the characterization factors for this category (Pettersen and Hertwich 2008). In addition to losses, processes included are for lines—production of materials for foundations, masts, conductors, and insulators and for cables—production of cable and cable trace. Installation (excavation, etc.) use/maintenance (replacement of parts, inspections) and end of life are also included for both overhead and cable systems. Recycling is modeled as suggested by Ecoinvent, i.e., to model recycling of steel, pig iron is used as avoided product and scrap iron as an input, and a similar approach is used for modeling recycling of other metals.

Table 1 List of components under scope in the paper

150 kV overhead line
400 kV overhead line
150 kV land cable (oil)
150 kV sea cable (oil)
HVDC overhead line
HVDC land cable
HVDC sea cable

2.3 LCI data quality and representativeness

The LCI data collected are subject to data availability which will determine its technological, geographical, and time-related representativeness (European Commission 2010). The data collected refer to power lines and cables installed in Denmark. As for materials, the inventories are quite similar to the ones found in other data sources

Table 2 Contribution of power losses to the total impact scores for each impact category (in percentage)

Impact category	150 kV overhead	150 kV land cable	150 kV sea cable
Climate change	99	96	97
Fossil depletion	99	84	96
Freshwater ecotoxicity	95	92	83
Freshwater eutrophication	>99	94	94
Human toxicity	99	84	83
Marine eutrophication	99	95	96
Metal depletion	34	7	5
Ozone depletion	98	71	92
Particulate matter form	98	90	90
Photochemical oxidant	99	88	93
Terrestrial acidification	98	89	92
Terrestrial ecotoxicity	98	84	88

(Harrison et al. 2010; Worzyk 2009) which indicate that the cable/line constructions assumed are quite average. We expect that installation will differ according to the region where lines/cables are going to be mounted, for example granite and chalk would be different to excavate. However, this and other studies (Harrison et al. 2010) have concluded that this represents a modest share of total infrastructure-related impacts. For the production of materials (steel, copper, etc.), we have selected, whenever possible, processes which represent European production. Exceptionally, some processes in the Ecoinvent 2.2 database (Ecoinvent Centre 2007a) are only available as average Swiss or global production, and those were picked instead. Since the majority of processes picked from the database reflect a European context, this should be taken into account when applying these results to other technological or regional contexts. However, since detailed life cycle inventories for all components are provided in the supplemental information section, it is possible for the reader to obtain these results for different contexts, for example, by using different electricity mixes for the power losses.

3 Results

3.1 Contribution of power losses

The contribution of power losses to the overall environmental impacts of three types of systems is presented in Table 2. Under the assumption of average European mix,

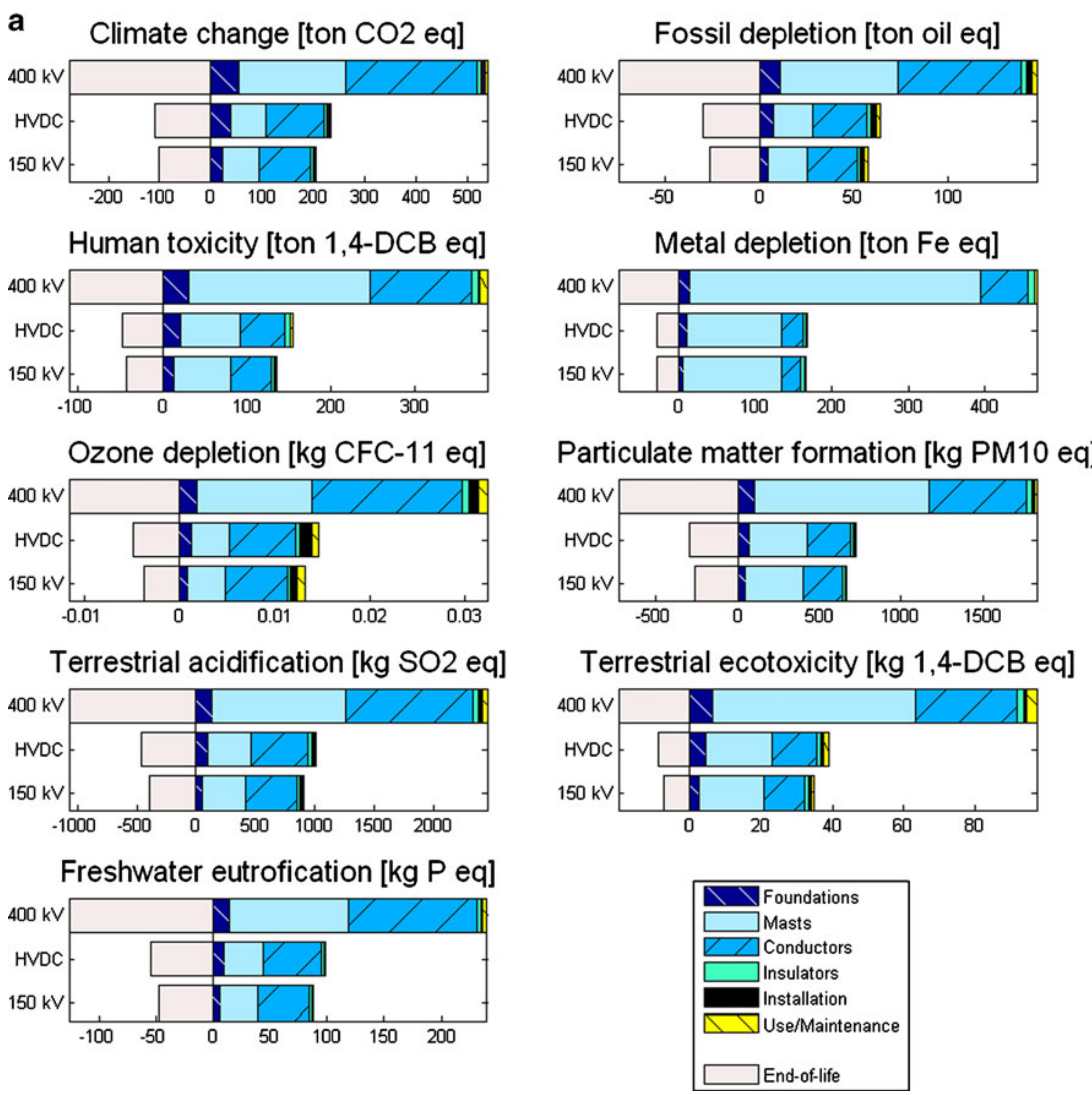

Fig. 1 **a** Breakdown of impacts per km associated with infrastructure processes for overhead lines—150 kV, 400 kV and HVDC—for different impact categories. **b** Breakdown of impacts per km associated with infrastructure processes for land and subsea power cables—150 kV and HVDC land cable, and 150 kV and HVDC sea cables—for different impact categories

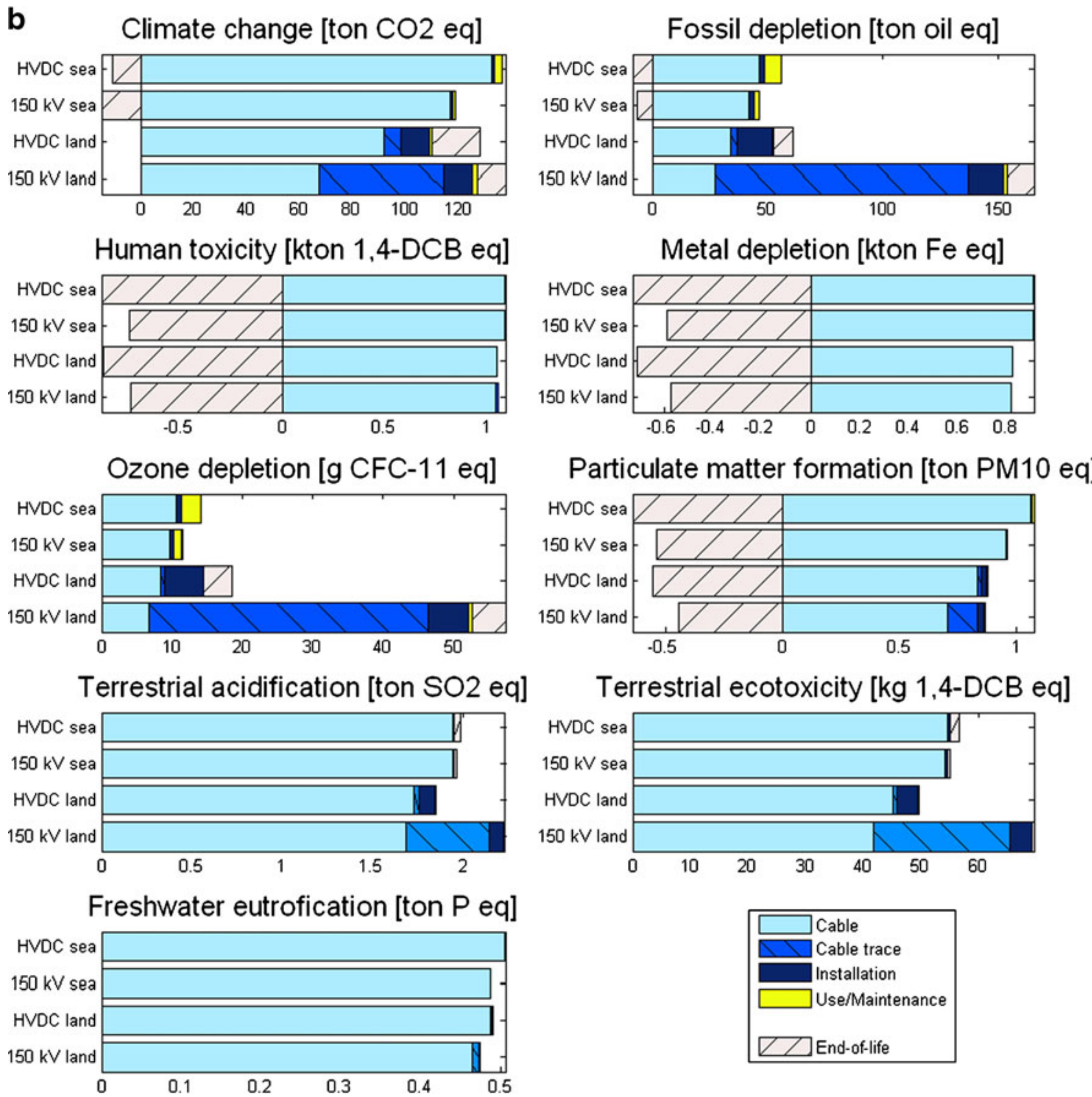

Fig. 1 (continued)

the results show a clear dominance of losses for all categories, with the exception of metal depletion, for which production of materials is the most relevant process.

3.2 Infrastructure processes contribution

Figure 1 shows the contribution of the different processes related to infrastructure to the components impacts. Figure 1a shows the results for overhead lines, while Fig. 1b shows the results of cables—subsea and underground. Starting with the analysis of overhead lines, the results show that for all impact categories, the materials for masts and conductors are dominant processes. Conductors and masts require large amounts of metals (Tables S5–S10), in particular steel and aluminum, which explains the high scores for these structures. The impact of masts—steel—is particularly high, as compared to other processes, for the category of metal depletion. The foundations, although requiring hundreds of tons of concrete per kilometer, come third in order of impact. Installation activities, resulting from transportation of materials and personnel to the construction site and excavation, etc., are found to have a very small share of total impacts. Use and maintenance operations contribute mostly to climate change and ozone depletion. These impacts are caused by replacement of parts and transportation activities for inspection, etc. The end of life has a negative contribution in all impact categories, which means that the benefits of recycling of metal parts in the masts and conductors (steel, aluminum, and zinc) outweigh the sum of impacts generated by other end of life processes, such as landfill (for foundation components), incineration of mineral oil, and transportation activities

associated with dismantling. Figure 1b shows the breakdown of impacts related to the infrastructure for the power cables—underground and subsea. For land cables, the inventories assume that they are to be installed in city areas. This requires removal of old asphalt and building a new layer of sand, cement, and asphalt where the cable is to be installed. The layer of sand, cement, and asphalt is designated as cable trace. For all cable types, cable material production is a dominant process. The materials in land and sea cables are similar (copper, lead, etc.), but the subsea equipment requires also large amounts of steel for armoring (Tables S11–S17), which contributes to high scores related to cable production in sea cables. For land cables, the cable trace and in particular production of asphalt are relevant processes for climate change, fossil depletion, ozone layer depletion, and terrestrial ecotoxicity. For land cables and for the categories of climate change, fossil depletion, and ozone depletion, the impacts of end of life represent a cost rather than a benefit. This indicates that, for these categories, recycling does not compensate for the impacts caused by the remaining processes in this phase. For sea cables, recycling shows benefits in the categories of metal depletion, human toxicity, particulate matter formation, fossil depletion, and climate change. For the remaining categories, recycling of sea cables does not compensate for other impacts caused at end of life. One process which was found to have a high impact for the end of life of land cables was the treatment of oil-impregnated paper, which according to Eltra (1999d) should be incinerated. This process has a high impact, especially for climate change. Processes related to use and maintenance of land cables, including direct emissions of mineral oil to the soil due to leakages and transportation activities, were found not to contribute significantly to the share of total impacts. The share of use and maintenance for total impacts, including leakages of oil to water and transportation activities, is higher for sea cables.

4 Uncertainty and limitations

Here we discuss some sources of uncertainty and limitations of this study. One limitation originates from how well it is possible to match the modeled processes with the ones available in Ecoinvent 2.2. The most suitable match was found for most processes, but a few limitations remain, for example recycling of asphalt is not available and this was instead modeled as disposal of asphalt to landfill. The end-of-life scenarios for the sea cables assume that they are recovered at the end of life, their components dismantled, and the waste treated according to the information on the reports (Eltra 1999a, b, c, d, e, f). Nevertheless, sea cables are not always dismantled nor their components recycled (Worzyk 2009), but they are often simply left at the seabed once not in use. Detailed information about practices in disposal and end of life treatment of lines and cables should therefore be obtained for each case and each situation modeled accordingly. Finally, power grid systems and in particular power lines and cables cause a variety of other environmental impacts which are not evaluated in this assessment, such as electromagnetic impacts, land use, visual impacts, noise and impacts to flora and fauna.

5 Conclusions and recommendations

The paper provides inventories for lines and cables used for power transmission, together with estimated data on power losses. The inventories identify important processes causing impacts for this type of equipment and provide data which can be useful in future LCA studies where it is necessary to model a customized grid connection. Despite a number of assumptions used here (average European power mix, materials produced in Europe, estimation of losses and loads in lines, etc.), the inventories are provided separately for each process, so the reader can make the required substitutions and obtain similar results for a particular case study. Overall, T&D can represent 10% of impacts for the complete power generation and supply chain (Cigré 2004a). Even if this percentage could be lower or higher depending on the electricity mix in case, T&D is still an important process and should be taken into account for the total impacts from the electricity sector.

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